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Woods Hole Oceanographic Institution

IMPACTS OF LARGE SCALE
AQUATIC BIOMASS SYSTEMS

by

Thomas Hruby

March 1978

TECHNICAL REPORT

Prepared with funds from the Pew Memorial Trust and by the Department of Commerce, NOAA Office of Sea Grant under Grant #04-7-158-44104 and the Institution's Marine Policy and Ocean Management Program.

WOODS HOLE, MASSACHUSETTS 02543

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Approved for Distribution ______________________
Dr. Robert W. Morse
Associate Director and Dean

PREFACE

This report was prepared for the Sea Grant Collegium Symposium/Workshop on the 'Economics and Engineering of Large Scale Algal Biomass Systems' held on January 24-25, 1978, at the Massachusetts Institute of Technology. It will be included as a chapter in <u>Cost Analysis of Algal Biomass Systems</u> (ed. E. Ashare), which will be available through N.T.I.S. in summer, 1978.

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INTRODUCTION

The difficulties inherent in collecting, storing, and distributing direct solar energy have provided the impetus for an increasing interest in capturing solar energy in the form of plant biomass. In response to this interest the Department of Energy is sponsoring a program in Fuels from Biomass with a goal of investigating sources of energy on a scale that would meet 5% to 10% of national energy needs by 1990. Sources being investigated include the large-scale culture of woody plants, aquatic plants, and algae, and using the organic residues from agriculture and the lumber industry. Energy would be extracted from biomass by burning or by reducing the organic material to methane (natural gas) through bacterial fermentation.

However, if plant biomass is to provide even a small fraction of the U.S. energy requirements large areas on the earth's surface will be required. For example, the culture of seaweeds over 10,000 square miles of ocean surface would produce only enough biomass to replace 5% of the national energy needs, and the total U.S. annual production of plant biomass (food, fiber, paper, lumber) would meet only 25% of the current requirements if converted to energy (Burwell, 1978).

Any activity undertaken by man on the scale necessary to produce usable energy from plant biomass carries with it the possibilities of a serious upset in the natural and human environments. It is the purpose of this report to consider the environmental impact of systems proposed for the large-scale culture of algae and other aquatic plants. In view of the present legal requirements and the general concern for the quality of life, the possible impacts of a system may be critical in determining the final choice of design. By understanding the dangers posed, long and costly delays may be avoided in developing this new energy resource.

Several different, and rather complex, systems are being considered for the culture of algae and other aquatic plants on the open ocean, the coasts, and on land. Since these share some of the same subsystems the impacts of algal biomass production will be considered in terms of these subsystems. Although specific impacts can be quantified only after a design and location have been chosen, it is possible at this stage in the planning process to determine the areas where dangers exist and where additional research is needed. Only the primary impacts will be considered in this report, and many of those predicted can only be considered as hypotheses since the basic scientific information necessary for accurate estimates on environmental dangers is often lacking. In addition, it should be remembered that developing any industry on the scale proposed may have a profound influence on the social and economic fabric of the nation; along with additional environmental effects resulting from the subsidiary industries that will be stimulated.

OPEN OCEAN SYSTEMS

A. General considerations:

Any structures of the size contemplated will reduce water circulation, even if placed on the open ocean. Wind generated waves will be damped out, and ocean currents may be slowed by the drag produced. These factors could change prevailing weather patterns, but quantitative estimates will require detailed data from each location and comprehensive simulation models.

Depending on the materials used in constructing the algal farms, numerous chemicals will be leached into the sea from the farm structures. In addition to the slow release of possibly toxic metals from supports and from antifouling paints, organic chemicals will be leached from the synthetic lines used in supporting the algae. At present little is known about the dangers of many compounds leached from synthetic fibers, but the indications are that toxic chemicals will be released. Nylon was proposed by Wilcox (1976) for his open ocean farm and is being used in the quarter acre *Macrocystis* farm being developed by General Electric. Although this polymer is fairly stable, it will release aldehydes (formaldehyde, etc.) on photodegradation (I.K. Miller, I.E. DuPont de Nemours Co., personal communication). PCB's which have been used as plasticizers in PVC polymers are known to be toxic and non-biodegradable (Hutzinger, et al., 1974). In addition, the entire class of aromatic polymers such as KEVLAR[R] may have adverse impacts on oceanic ecosystems for many aromatic compounds are highly toxic and carcinogenic (CEQ, 1975).

In addition to the chemicals leached from farm structures, dissolved organic compounds will be released by the algae at rates as high as 40% of the net carbon fixed (Sieburth, 1969). In brown seaweeds the exudations are toxic to some marine organisms (Plaice larvae - Sieburth and Jensen, 1969; epiphytic animals - Sieburth and Conover, 1965; planktonic animals - Conover and Sieburth, 1966; and bacteria - Scotten, 1971). The toxic compounds exuded are probably phenols (Sieburth and Jensen, 1969).

Calculations based on the available data suggest that toxicity resulting from organic exudation will be a problem in algal farms if brown algae are used. In Macrocystis, Scotten, (1971) found that bacterial numbers were reduced by 94% when placed in the exudate from 20 mg of tissue in 100 ml of enriched seawater. This density of plant material is 1/10 of the density proposed for the open ocean farms. By assuming that the physiological behaviour of Macrocystis will not be too different from that of related species known to produce phenols, the estimated release on a farm would be approximately 0.1 ppm hr^{-1} (see Appendix A for calculations). The actual phenol concentrations in the water will then depend on the turnover rate as shown in Figure 1. For the design using upwelled waters a turnover rate of 10 hours (approximately 3000 gal $min^{-1} acre^{-1}$) has been proposed, which would result in an approximate phenol concentration of 1 ppm.

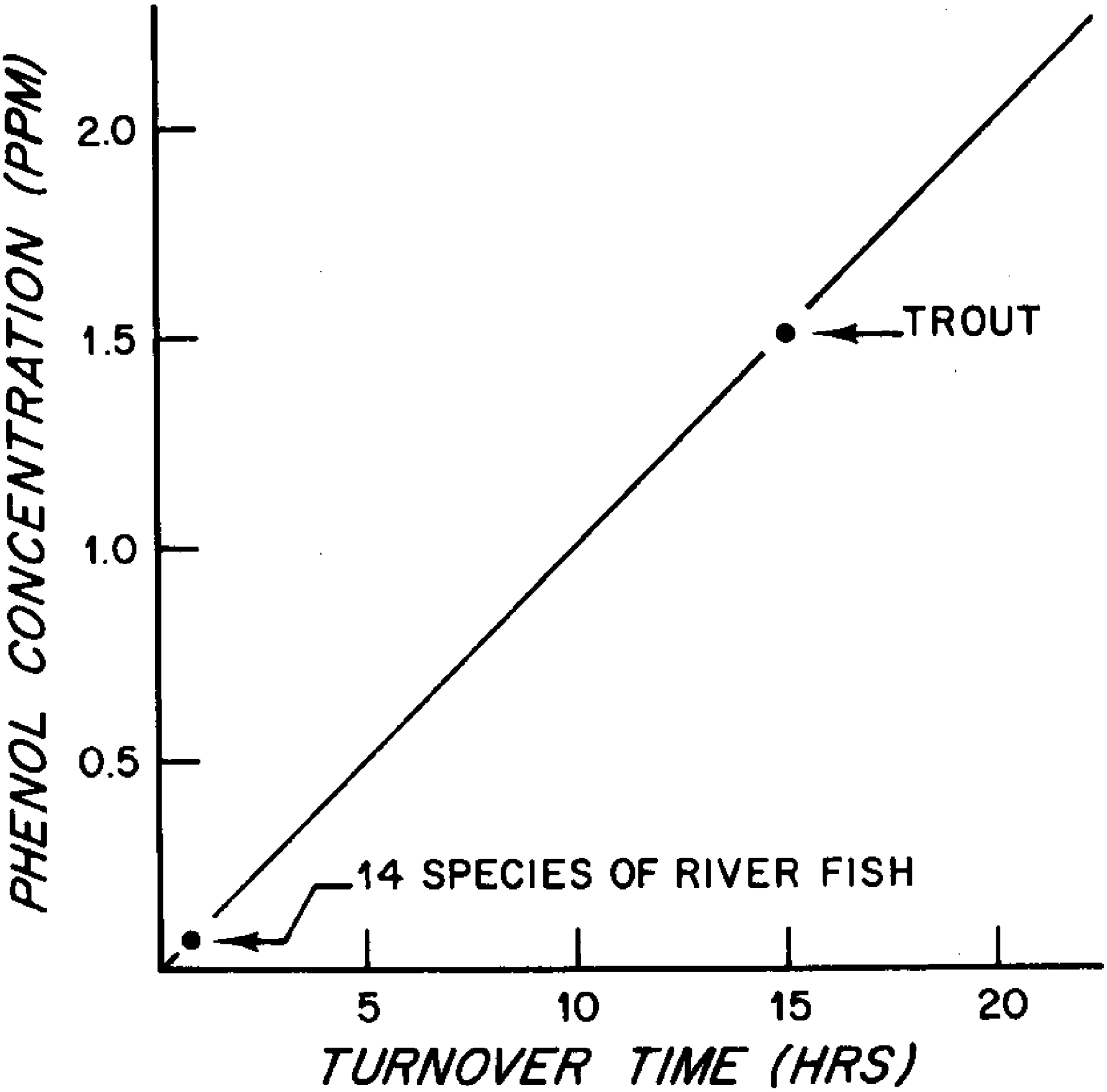

Figure 1: Expected phenol concentrations in a Macrocystis farm as a function of the turnover time of the surface water. The two points mark phenol concentrations which affect the fish mentioned as reported by Mitrovic (1972).

In natural beds of Macrocystis the turnover rate is approximately 20 hours (W. J. North, personal communication), and the animals adapted to living in kelp beds will probably survive on an algal farm fertilized by upwelling. However, phenol toxicity may be a significant problem if the open ocean communities, which are not adapted to high levels of phenols, become contaminated. Although little is known about the sensitivity of plankton to phenols, fish not associated with kelp beds are sensitive to very low concentrations (reviewed by Mitrovic, 1972). To indicate how turnover may be a critical factor in phenol toxicity the concentrations found to affect some species of fish are marked in Figure 1.

Furthermore, phenol concentrations on algal farms not fertilized by upwelling will probably reach much higher levels than the predicted 1 ppm because the natural turnover in the open ocean is slower than in the coastal areas.

The large algal farms can be expected to have a negative impact on commercial shipping if they create barriers to the free movement of ships. In areas of heavy ship traffic such as the Caribbean and the Atlantic, finding locations which do not conflict with shipping lanes may be difficult. Since recreational boating is also well developed and organized in the western Atlantic, strong opposition can be expected if farms are located in the path of well-known yacht races such as the Bermuda Cup.

To minimize the negative impact of open ocean farms on fishing, locations which are traditionally used as fishing grounds should be avoided. Since the U.S. has well-developed fishing industries in the Caribbean and off the California coast locating algal farms in these areas will be more difficult than in the subtropical Atlantic. On the other hand, if fish are maintained as a crop on the farm both commercial and sports fisheries might benefit.

Because so many factors are linked, the specific impact of the algal farms on other activities will vary greatly with location, and these can be assessed only on an individual basis. The attitudes and habits of merchant marine captains and the local fishermen will determine whether the farms will be considered favorably or unfavorably. Such attitudes can be determined only on a local level by holding hearings and making appropriate surveys, and to avoid problems the impacted parties should participate in the planning and decision making.

B. Design alternative: nutrient enrichment by upwelling.

There are several impacts, all negative, which can be predicted for the upwelling of large volumes of seawater.

First, there are several dangers associated with the temperature difference that will exist between upwelled waters and those present on the surface. Large fog banks are created in natural upwelling regions as warm moist air is blown over the cooler deep water, such as the region off California, and similar conditions will probably prevail in areas of artificial upwelling. In addition to creating a navigation hazard, fog banks can reduce the amount of sunlight reaching the surface by 70% (Pickard, 1963). This will reduce the plant productivity within the farm and in adjacent surface waters. However, quantitative estimates of productivity losses will have to wait for detailed hydrographic and biological data from each site.

Wilcox (1976) has hypothesized that the extensive fog banks might significantly reduce the earth's surface temperature by reflecting large amounts of sunlight. However, calculations based on total energy flux suggest that 10,000 square miles of fog (100 farm units) between 30^{o}N and 30^{o}S will lower the earth's temperature by only 0.01^{o}C (see Appendix B for calculations).

Secondly, the upwelling of deep waters would entrain with it all organisms which cannot swim faster than the inflow velocities, and these would include bacteria, protozoans, a wide variety of invertebrates, and possibly even some fish. It has been the experience in oceanographic sampling that organisms brought up from deep water usually die, and a similar phenomenon can be expected if water is upwelled. Death seems to be caused by the rapid pressure changes which occur when water is brought to the surface, and thus small diameter pipes with rapid flow rates will have a worse impact than large diameter pipes with slower flow rates. Based on the data available for the biomass in the region of the Atlantic Slope (Wiebe, et al., 1976), it is estimated that 4.4 metric tons of animal biomass will be brought to the surface in a day on a 100 square mile farm requiring 3000 gal $min^{-1} acre^{-1}$ located off our Atlantic Coast. If this extrapolated to 100 farm units the estimate comes out to be a staggering 160,000 tons per year. This is equivalent to the total U.S. landings of Pacific Salmon in 1976 (U.S.D.C., 1976). It is clear that no single mesopelagic region can long support such a depletion without undergoing major changes, and the calculation indicates that upwelling will quickly remove animal populations in the water under the farm.

If mesopelagic fish become economically important to the U.S. fishing industry, as they have for the Japanese, the upwelling could have a negative impact on commercial fishing by destroying the food chain.

In the cold upwelled water passing through the algae animal populations will probably remain sparse. Few living organisms will be brought from the deep, and the available data suggests that horizontal thermal and density gradients, such as those produced by natural upwelling or oceanic circulation, form a barrier to animal movements (Marr, 1962; Marti, 1969; Wiebe, et al., 1976). Thus, species from the warmer surface water will not migrate into the algal farm fertilized by upwelling, and animals will have to be stocked artificially to fully utilize the incidental production (diatoms, bacteria, etc.).

C. Design alternative: nutrient enrichment by recycled fermentation waste

The major problem foreseen in providing nutrients by recycling fermentation waste is toxicity from accumulations of heavy metals. Algae concentrate heavy metals present in seawater by factors ranging from 40 to 100,000 (Goldberg, 1965). It can therefore be expected that cultivated plants will absorb both the metal present in the seawater and any present in the residues used as fertilizers. For example, copper concentrations in dried algae are approximately 1 ppm (Chapman, 1970). The metal will remain in the residues from bacterial fermentation unless it is removed in the process of sollubilizing the nutrients. Since copper is toxic for *Macrocystis* at levels of 0.1 ppm (Clendening, 1958) and it is used as a general algicide at 1-2 ppm (Krauss, 1962), there will be little difference between copper concentrations in untreated residues and the levels at which it becomes toxic if applied externally (toxicity of internal and external copper concentrations are not comparable because the metabolic pathways may be different in each case). In addition to being toxic for seaweeds, untreated fermentation waste may also be toxic to other organisms in the farms. Copper was found to affect Pink shrimp at 0.14 ppm (Portman, 1968) and Brown shrimp at 10 ppm

(Portman, 1972). Other potentially dangerous metals to be found in the residues are Chromium, Cadmium, Lead, Cobalt, and Mercury.

On the positive side, the fermentation wastes will contain large quantities of organic material (approximately 50% of the total harvested). The organic material not consumed in the vicinity of the farms will sink towards the bottom and provide food for deep water organisms and those living on the bottom. If the organic matter is not contaminated with heavy metals, these populations will probably increase and provide a good source for a new fishery. As mentioned previously, the Japanese have already begun to exploit the mesopelagic fish.

D. Design alternative: nutrient enrichment by fertilizers.

By fertilizing the algal farms with artificial nutrients it will be possible to avoid the negative impacts predicted for the other two methods. However, the problem with using fertilizers is their availability and cost. At present the minimum nutrient requirements for one farm of 100 mi^2 producing 30 tons $acre^{-1}$ yr^{-1} of *Macrocystis* reporesents 0.35% of the total U.S. annual consumption of 9,384,000 tons (U.N. Statistical Yearbook, 1976). One hundred farm units would therefore require 35% of the annual consumption, and the diversion of such amounts from agriculture to aquaculture will have such an adverse effect on our food production that the method is not feasible for the present.

NEARSHORE SYSTEMS

A. General considerations

To decrease engineering costs it has been suggested that algal farms be located near the coast where the water is shallow, or in bays where the culture system can be enclosed by breakwaters or dykes. Although nearshore systems may prove to be economically feasible their impacts would be significant, for the development of farms would conflict with other uses of coastal waters by eliminating large areas from the public domain. At present we use coastal waters for a wide variety of activities including:

1) Public transport
2) Waterborne commerce
3) Naval activities
4) Commercial fishing
5) Sewage dilution and industrial cooling
6) Other forms of aquaculture
7) Recreation (sports fishing, boating, waterfront parks)
8) Ecological and scientific reserves

As an example of the problems involved in siting a farm in our coastal waters one can hypothesize a 100 square mile farm in southern Cape Cod Bay. As shown in Figure 2, much of the bottom in the area suggested for the farm contains harvestable shellfish beds which would become inaccessible in the presence of a farm.

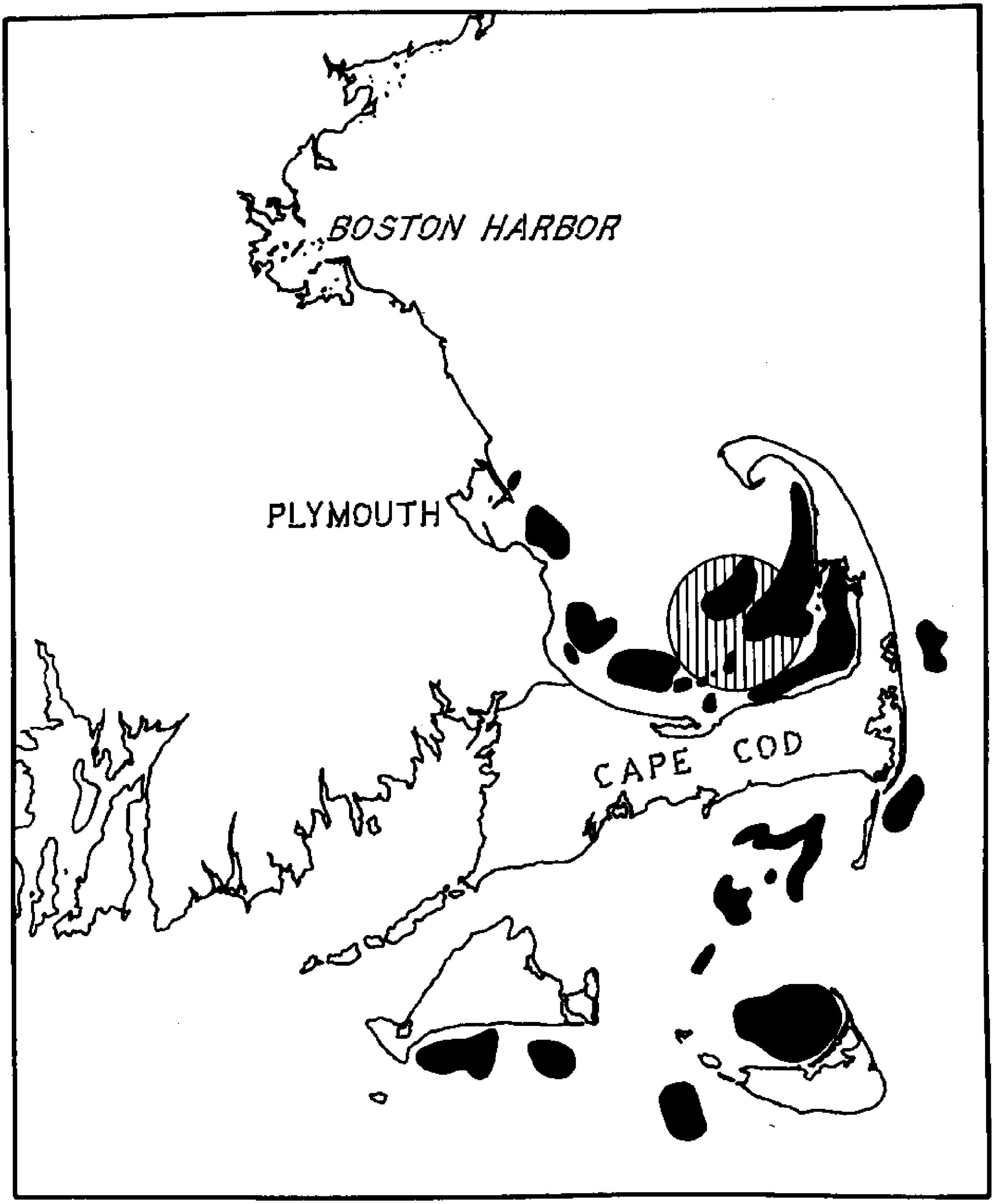

Figure 2: A possible nearshore location for a 100 mi^2 farm (shaded circle) superimposed on a map of existing shellfish beds (solid black areas, from Massachusetts CZM Plan, 1977)

Also within the area are 4 developed harbors, approximately 16 marinas and boat ramps, 41 public beaches and one recreational viewpoint (data on coastal activities from the Massachusetts CZM Plan, 1977). All these activities will be impacted by the presence of the farms. Access to harbors and boat ramps will be reduced, if not impaired. Public beaches will lose their scenic attributes, and possibly even their water quality. Furthermore, the location is close to a site recommended for the disposal of dredged material, and it is near an area of heavy commercial oil traffic with risks of oil pollution (an oil spill could destroy an entire crop). Finally, the site is in the middle of a zone designated as a sanctuary. Other coastal locations will have different conflicts, but they can be expected to be of a similar magnitude.

Although the impacts on human activities will be the most evident and thus the most publicized effects, the nearshore farms will also have an impact on the natural environment, whereever they are located.

The algae and their supporting structures will damp out incoming waves, and thus reduce longshore water movement (Zenkovich, 1971). As a result, the farms will act as sediment traps. The reduction of water movement might also slow the dispersal of freshwater coming from land, thus reducing the salinity in the vicinity of the farms. With the farms acting as sediment traps, the salinity being reduced, and the production of large amounts of organic compounds by the algae, the net effect of coastal farms will be to produce a salt-marsh like environment regardless of the original conditions in the area.

The biological effects of a coastal algal farm can be evaluated only after specific sites have been chosen because our coastal ecosystems are highly varied and depend on many factors such as climate, type of bottom available, amount of turbulence, seawater salinity, or the presence of suspended sediments. However in trying to assess the impact of an algal farm there are some basic questions which need to be considered in all locations, and these are as follows:

What will be the effect of--

1) reducing the sunlight reaching the bottom,

2) changing the habitat of free swimming animals,

3) increasing the load of organic matter to the water column and to the seabed,

4) increasing nutrient concentrations in the water, and

5) changing the patterns of water circulation (this is important in the recruitment of oysters and other shellfish).

More basic research is needed to answer most of these questions, so an evaluation of impacts at this time would be premature. However, the information available suggests that major changes will occur in biological communities. Off California the development of natural *Macrocystis* 'forests' was found to change the plant and animal populations in the immediate area (North, 1971; Foster, 1975). In the vicinity of sewer outfalls, where the levels of nutrients and organic matter are high, species dominance was found to change from longer-lived species to those with shorter life spans (M. Littler, unpublished report). Unplanned introductions of algal species, such as Sargassum in Britain (Fletcher and Fletcher, 1975) and Codium in Chesapeake Bay (Dawson, 1966) have had such highly adverse impacts on the environment that many algologists, including the author, voted a resolution opposing the introduction of Macrocystis in French coastal waters at the 1976 meeting of the British Phycological Society.

B. Design alternatives: nutrient enrichment by upwelling and recycling.

The effects of nutrient enrichment in the coastal environment are similar to those already mentioned for the open ocean. In this case, however, most of the organic matter which sinks out of the surface layers will reach the bottom, which may then become anaerobic. Since the nearshore environment is also more restricted than the open ocean, the dispersal of toxic chemicals will be slower, and dangerous levels may be reached sooner than in the open ocean.

C. Design alternatives: Breakwaters and floating rafts.

Since breakwaters reduce water circulation more than rafts, the former will have a stronger impact on sediment transport. Protected areas behind breakwaters quickly fill with sediments in areas of longshore transport. A classic example of this problem is the Santa Barbara breakwater which was built in an area where the sediment transport was 300,000 cubic yards per year (Bascomb, 1964). Most of this sand collects behind the breakwater, and has to be dredged out. Breakwaters constructed to contain algal farms pose a similar problem.

LAND BASED SYSTEMS

As with nearshore farms, ones on land will compete with other activities for the basic resources of land and water. The severity of the impact will depend on present, or future, uses of the same resources. Since an energy program based on plant biomass production will probably have a low priority for the voting public (compared to industry, agriculture, or recreation) the farms will have to be located where their impact on other activities will be the lowest, regardless of the additional costs this may create.

Ultimately the impacts of pond culture on the natural environment will also be negligible because fully closed systems can be built. However, the cost of assuring that no polluting substances are released during growth and energy production will be high. It is expected that discharges of contaminated water and fermentation residues will be the maximum allowable by law. The problem areas in terms of environmental quality are: 1) toxic metals in the fermentation waste from marine algae, 2) the disposal of unutilized fermentation waste and sediments from the ponds, 3) the soluble organic compounds produced by the plants, and 4) the build up of inorganic salts in ponds where net evaporation is higher than the rainfall. However, some of the potential pollution problems may be minimized by choosing designs which decrease the pollution. For example, both microscopic and large algae have been found to release organic compounds, but the actual compounds vary greatly with species (Lewin, 1962, Sieburth, 1969). To minimize the total cost of production it might be advantageous to consider species which have the least toxic exudations, even if their overall productivity is not the highest. In this respect the green algae or water hyacinths may be the best suited for pond culture.

CONCLUSIONS

The impacts discussed in this report are summarized in Table 1. All systems are potentially dangerous for the natural and human environments, but those for the land based farms are more dependent on the exact design of the ponds and their processing units than either the open ocean or nearshore systems. Therefore, if environmental impacts are used as criteria in the choice of a system, algae grown in ponds are better suited for development as a biomass source than either the open ocean or coastal systems. Important reductions in the cost of maintaining environmental quality might be achieved if the system is designed to minimize external pollution rather than optimizing production, and it might also be highly cost effective to develop efficient methods for extracting the complex organic molecules produced by the plants.

Table 1

Impact matrices for algal biomass systems located on the open ocean (A), near the shore (B), and on land (C). A plus sign [+] indicates a positive (good) impact, a minus sign [-] a negative (adverse) impact, a double minus [--] an adverse impact of such magnitude that the design alternative is not feasible, and a zero [0] indicates that there is little or no impact. Parentheses () indicate possible impacts evaluated on very insufficient data, and question marks [?] indicate that the impact cannot be evaluated, either for lack of information or because the design alternative have both positive and negative impacts.

IMPACT PRODUCING FACTOR		NATURAL ENVIRONMENT				OTHER ACTIVITIES					
		Climate & Circulation	Sediment transport	Water quality	Biological communities	Use of available resources	Commerce	Industry	Farming (fishing)	Recreation	Preservation
	A. Open Ocean Systems										
Design	Floating structures	(-)	0	-	+	-	-	0	+	?	0
Nutrient Source	Fertilization by upwelling	-	0	-	-	0	0	0	-	0	0
	" " recycling waste	0	0	-	(-)	0	0	0	+	0	0
	" " artificial nutrients	0	0	0	+	--	0	0	+	0	0
Product	Macroscopic algae	0	0	-	?	0	0	0	+	0	0
	B. Nearshore Systems										
Design	Floating structures	-	-	-	+	-	-	(-)	?	-	-
	Breakwaters	--	--	0	+	0	--	-	0	-	-
Nutrient Source	Fertilization by upwelling	-	0	-	-	0	0	0	(-)	0	-
	" " recycling waste	0	(-)	-	-	0	0	0	+	(-)	-
	" " artificial nutrients	0	0	-	-	--	0	0	+	0	-
Product	Macroscopic algae	0	0	-	?	0	0	0	+	0	0
	Sea grasses	0	-	0	?	0	0	0	+	0	0
	C. Land Systems										
Design	Ponds on:										
	Coasts	0	0	0	?	--	-	-	-	-	-
	Deserts	(+)	0	0	(+)	(-)	0	0	(-)	-	-
Nutrient Source	Fertilization by recycled wastes	0	0	-	-	0	0	0	0	0	-
	" " artificial nutrients	0	0	-	-	--	0	0	0	0	-
Product	Macroscopic algae	0	0	-	-	0	0	0	0	0	0
	Microscopic algae	0	0	-	0	0	0	0	0	0	0
	Aquatic plants	0	0	?	?	0	0	0	0	0	0

Appendix A: Estimate of phenol production in algal farms.

In *Ascophyllum nodosum*, *Fucus vesiculosus*, *Laminaria digitata*, and *L. agardhii*, which are similar to *Macrocysits pyrifera*, phenol exudation is approximately 10 mg hr^{-1} ($\pm$ 5mg) for every 100 g of dry alga (Sieburth, 1969). Since the dry weight of seaweeds is approximately 10% of its wet weight the release of phenols is 10 mg $hr^{-1}kg^{-1}$(wet). The standing stock of *Macrocystis* projected for an open ocean farm is $8.8 \cdot 10^4$kg $acre^{-1}$ which would result in a release of phenols at a rate of 0.88 kg $hr^{-1}acre^{-1}$. Assuming that 60 - 75% of the algal biomass is within 2 m of the surface, the amount of phenols released into the surface waters would be approximately $0.6 \cdot 10^{-7}$ kg $liter^{-1}$ hr^{-1} or roughly 0.1 ppm per hour.

Appendix B: Calculation of temperature reduction by fog banks.

One half of the earth's surface area lies between 30°N and 30°S, and about 60% of the solar radiation reaching the earth falls in this area (Pickard, 1963). One hundred farm units will cover 2.59 $10^4 km^2$ or 0.01% of the surface in the tropics. If farms decrease the amount of solar radiation reaching the earth by 70% the loss for the equatorial region would be 0.007% and for the earth as a whole 0.0042%. Assuming that the earth's mean temperature of 283°K is totally provided by the sun (Dietrich, 1957), a reduction in the incident radiation of 0.0042% would reduce the surface temperature by 0.012°C.

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13. Type of Report & Period Covered
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14.

15. Supplementary Notes

16. Abstracts

Several different, and rather complex, systems are being considered for the culture of algae and other aquatic plants on the open ocean, the coasts, and on land. Since these share some of the same subsystems, the impacts of algal biomass production will be considered in terms of these subsystems. Although specific impacts can be quantified only after a design and location have been chosen, it is possible at this stage in the planning process to determine the area where dangers exist and where additional research is needed. Only the primary impacts will be considered in this report, and many of those predicted can only be considered as hypotheses since the basic scientific information necessary for accurate estimates on environmental dangers is often lacking. In addition, it should be remembered that developing any industry on the scale proposed may have a profound influence on the social and economic fabric of the nation; along with additional (Cont.**)

17. Key Words and Document Analysis. 17a. Descriptors

1. Aquatic Biomass
2. Environmental Impacts
3. Alternative Energy Sources

17b. Identifiers/Open-Ended Terms

(Cont.**) environmental effects resulting from the subsidiary industries that will be stimulated.

17c. COSATI Field/Group

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